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UNITED STATES
DEPARTMENT OF THE INTERIOR
Geological Survey

PRELIMINARY INVESTIGATION OF LAND SUBSIDENCE IN THE SACRAMENTO VALLEY, CALIFORNIA

Prepared in cooperation with the
California Department of Water Resources

OPEN-FILE REPORT

Sacramento, California
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ILLUSTRATIONS

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ABSTRACT

Although a number of agencies have made leveling surveys in Sacramento Valley and a valleywide network of first- and second-order control exists, few areas have sufficient control for determining whether land subsidence has occurred and if so, how much, within the time span of vertical control. Available data suggest that 0.2 to 0.9 foot (0.06 to 0.3 m) of subsidence probably has occurred from 1935-42 to 1964 in an extensive agricultural area of heavy ground-water pumping between Zamora and Davis, and that as much as 2 feet (0.6 m) of subsidence has occurred in at least two areas of pumping overdraft--east of Zamora, and west of Arbuckle.

A comparison of maps showing long-term water-level decline and average annual ground-water pumpage indicates several other areas of probable subsidence. In six general areas--northwest of Sacramento; northeast of Sacramento; southeast of Yuba City; 10 miles (16 km) north of Willows; 20 miles (32 km) north of Willows; and especially in the Arbuckle area--ground-water declines have quite probably produced significant subsidence. In two areas of most intensive pumping, no long-term water-level declines have occurred, and no subsidence is indicated.

If problems of land subsidence are of concern in Sacramento Valley, and if estimates of historic subsidence or subsidence potential are needed, serious consideration should be given to a field program of basic-data collection. Second-order leveling along a few carefully selected lines of existing control, and the installation and operation of two or three compaction recorders in areas of continuing water-level decline, would provide helpful data for estimating past and future subsidence.

C-040801

INTRODUCTION

Unlike the San Joaquin Valley, ground-water levels in most of the Sacramento Valley have remained generally high during the past 50 years of agricultural development. Traversed by the largest river of the State--the Sacramento River and its tributaries--the irrigation demands of Sacramento Valley are supplied largely by surface streams and canals. Ground-water pumpage in Sacramento Valley in the mid-1960's was about 1.8 million acre-feet (2.2×10^9 m^3) per year (Mitten, 1971, 1972), about one-sixth the ground-water withdrawal of the San Joaquin Valley. In a few localities, however, intensive pumping has caused long-term declines of ground-water levels. In several of these areas of overdraft, and also in at least two of the numerous scattered gas fields, there is evidence of land subsidence probably caused by the fluid extractions. East of Zamora, for example, as much as 2 feet (0.6 m) of subsidence apparently has been caused by heavy pumping, and at several locations between Davis and Zamora subsidence exceeds 0.5 foot (0.15 m). At Arbuckle, and reportedly near Corning, local subsidence may be caused by gas-field withdrawals. In most of the valley, however, leveling data are too sparse to determine whether or not subsidence has occurred.

C-040802

Land subsidence, if occurring on a broad scale in Sacramento Valley, is of serious concern from several aspects. Many of the floodways, levees, and canals of the valley--traversing great distances and designed with very gentle gradients--may be seriously affected by even small elevation changes. Also, in managing the ground-water basin for cyclic storage, particularly with the possibility of large pumping drawdowns during future droughts, the likelihood of causing future subsidence is of prime interest. To know where subsidence has occurred in the valley, and the magnitude, rate, and causes of the subsidence is of interest to Federal, State, and local agencies.

Although many agencies have done leveling in Sacramento Valley, little of the data are adequate for interpreting subsidence. Most of the surveys have spanned only short distances and have tied to reference bench marks of uncertain elevation. To be meaningful, surveys must be of regional extent, reaching beyond areas of subsidence to relatively stable reference ties. The first leveling along a line of bench marks determines the relative elevation of the bench marks, and establishes a base from which future changes can be measured. Subsequent resurveys of these bench marks, again tied to the same relatively stable reference tie, are necessary before changes in elevations can be calculated. Although a rather extensive network of first- and second-order leveling exists in the Sacramento Valley, largely established before the heaviest ground-water development, many of the areas of overdraft are not traversed, and few of the lines have been resurveyed.

As part of the cooperative studies with the California Department of Water Resources, the U.S. Geological Survey was asked to make a preliminary investigation of subsidence in the Sacramento Valley. The purposes of the investigation were to determine the extent of regional leveling in the valley; to delineate the areas where repeated leveling indicates that subsidence has occurred; to map the areas of significant historic water-level decline, insofar as data are available; to show which of these have been traversed by repeated leveling; and to make a brief interpretation of the data available. Even though pertinent data were known to be sparse, this appraisal is a first step in understanding both historic changes or subsidence potential in the valley.

For a detailed discussion of the geologic features and ground-water storage capacity of the Sacramento Valley, reference is made to the report by Olmsted and Davis, 1961.

C-040804

EXTENT OF LEVELING BY THE NATIONAL GEODETIC SURVEY

Figure 1 shows the network of first- and second-order regional leveling

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Figure 1 near here.

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in Sacramento Valley by the National Geodetic Survey, a component of National Ocean Survey[1/] (formerly U.S. Coast and Geodetic Survey).

Footnote (p. 11b) near here.

Also shown, by letter designation, are the reaches of the net for which profiles of apparent change in elevation of the land surface are included in the report. This regional network is the base to which most of the surveys of other agencies over the years have been tied, and also, is the reference datum from which measured changes in this report have been calculated. Figure 2 shows the years of leveling on each of the survey

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Figure 2 near here.

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lines, and also the bench marks for which repeated leveling indicates significant change in land-surface elevation.

1/ The agency requests that all inquiries for geodetic control data (including vertical-control data) be directed to the National Geodetic Survey, Rockville, Maryland 20852, and advises that this name will replace Coast and Geodetic Survey on future publications. Accordingly, subsequent reference in this report is to the National Geodetic Survey.

C-040806

Published bench-mark elevations by the National Geodetic Survey, listed by line and number for the thirteen 30-minute quadrangles (fig. 2) in Sacramento Valley, are the basis for most of the leveling data in this report. After carefully reviewing the available leveling data, it is concluded that the first surveys on most of the lines (fig. 1) are an adequate and reliable base for measuring subsequent elevation changes of bench marks (see figs. 5-12). Published elevations for later resurveys along these lines, however, frequently do not reflect true elevation changes. Problems of using different reference ties in different parts of the valley, and procedures of adjusting the field data to obtain suitable survey closures, often have obscured or eliminated in the published data the changes in bench-mark elevations that have actually occurred. No attempt has been made in this study to reconcile any of these discrepancies or to reinterpret any of the published data. It is believed, however, that a relatively simple reinterpretation of the releveling data of the valley, possibly by the National Geodetic Survey if guidelines are provided, could eliminate many discrepancies in the existing data.

POSSIBLE CAUSES OF SUBSIDENCE

Of the five types of subsidence occurring in the San Joaquin Valley and Delta areas (Poland, Lofgren, Ireland, Pugh, 1973, p. 39), probably only three occur in Sacramento Valley. Listed in descending order of magnitude, these are: (1) subsidence caused by water-level decline and the consequent compaction of the water-bearing deposits; (2) subsidence related to gas-field fluid withdrawal; and (3) deep-seated tectonism. Little data are available to correlate subsidence with any of these causes, or to determine the magnitude and rate of subsidence taking place.

Because fluid-pressure declines result in increased effective stress (Lofgren, 1968), areas of fluid extraction are likely to subside if water levels decline significantly. In other areas studied, a rough rule of thumb suggests that 1 foot (0.3 m) of subsidence results for each 10 to 100 feet (3 to 30 m) of water-level decline below historic low levels (subsidence/head-decline ratio of 0.1 to 0.01).

Unfortunately, long-term water-level measurements in wells in most of Sacramento Valley are almost as sparse as the limited subsidence data. Figure 3 shows the long-term water-level trends at 13 locations and also

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Figure 3 near here.

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the areas where significant water-level decline is known to have occurred between 1912-13 (Bryan, 1923, pl. IV) and 1969. Thus, in at least five localities on both sides of the valley trough, water levels have declined from 40 to 110 feet (12 to 33 m) prior to 1969. Quite likely, measurable subsidence has occurred in each of these areas. Figure 3 also delineates the scattered gas fields in which subsidence, past or future, is a possibility.

Figure 4 shows the average annual ground-water pumpage for 1966-69

Figure 4 near here.

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by township throughout Sacramento Valley, as estimated by the Geological Survey from electrical power and meter data (Mitten, 1971, 1972). In this illustration, pumpage is reported in feet of water [acre-feet per township ÷ 23,040 (acres per township) = feet], and each township average is shown as a point value at the center of the township for simplicity in contouring. Thus, in T. 9 N., R. 5 E., a few miles northeast of Sacramento, a 1966-69 average of 1.6 feet (0.49 m) of water (1.6 acre-feet per acre) was pumped each year. In this same area, from 20 to more than 50 feet (6 to more than 15 m) of water-level decline (fig. 3) occurred from 1912-13 to 1969.

Comparing areas of intensive pumping (fig. 4) with areas of significant long-term water-level decline (fig. 3), in four localities there is some coincidence. Apparently, these are areas of limited recharge and pumping overdraft. In other areas, recharge is apparently sufficient to replenish the ground-water reservoir and prevent long-term water-level declines. It is suggested that in six general areas--northwest and northeast of Sacramento, southeast of Yuba City, 10 miles (16 km) north and 20 miles (32 km) north of Willows, and especially in the Arbuckle area 12 miles (19 km) south of Williams--ground-water declines have quite likely produced a significant amount of subsidence. In the two areas of most intensive pumping in the Sacramento Valley, south and southwest of Chico, no long-term decline of water levels has occurred.

AREAS OF APPARENT SUBSIDENCE

As noted earlier, few areas in the Sacramento Valley have sufficient leveling control to permit calculating the amount or extent of subsidence that may have occurred. In a few localities, however, repeated leveling does indicate definite changes in land-surface elevation.

Figures 5 through 12 show profiles of apparent change in land-surface elevation during various time intervals between levelings. For location of these profiles, see figure 1. Data used in preparing these profiles are principally bench-mark elevations of the National Geodetic Survey. Because of adjustment problems in the basic data, elevation changes shown in these profiles are approximate and indicate only the order of magnitude of relative change suggested by the data. Figure 5 suggests that from 0.2 to 0.9 foot

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Figure 5 near here.

(0.06 to 0.3 m) of subsidence took place on the line from Zamora to Davis (fig. 1) between 1935-42 and 1964. A corresponding long-term water-level decline of as much as 20 feet (6 m) (fig. 3), indicates a very rough subsidence/head-decline ratio of about 0.03 to 0.05. Figure 6 shows the apparent change

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Figure 6 near here.

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in elevation of the land surface along line C-A (fig. 1) from relatively stable rocks west of Madison to an area of active subsidence at Zamora. These profiles suggest 0.2 to 0.3 foot (0.06 to 0.09 m) of subsidence in the Madison area from 1949 to 1966, and more than 0.6 foot (0.2 m) of subsidence at bench mark A644 at Zamora from 1949 to 1964. However, the differentials at bench marks M849 and N849 between 1964 and 1966 suggest there may be about 0.2 foot (0.06 m) discrepancy in the datums of the two surveys.

Figure 7 shows the change from 1949 to 1967 from Zamora northward

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Figure 7 near here.

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to Williams, where subsidence ranged from about 0.2 to 0.8 foot (0.06 to 0.2 m) during the 18 years. At Arbuckle, water levels declined more than 40 feet (12 m) (fig. 3) and bench mark T200 subsided about 0.9 foot (0.3 m) from 1949 to 1967, suggesting a subsidence/head-decline ratio of about 0.02. A few miles west of Arbuckle, where water levels declined more than 110 feet (33 m) from 1912-13 to 1967, subsidence probably exceeded 2 feet (0.6 m) during this same period, assuming the same 0.02 subsidence/head-decline ratio. It is interesting that both hydrographs for wells in the Arbuckle area (fig. 3) indicate a rising water-level trend since 1967.

C-040814

From Willows to Williams (fig. 8), and westward from Williams (fig. 9)

Figures 8 and 9 near here.

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apparent subsidence was generally less than 0.2 foot (0.06 m) from 1949 to 1967. On the lines running west from Willows (fig. 10) and west from

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Figure 10 near here.

Corning (fig. 11), the apparent uplift of the land surface between 1949 and

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Figure 11 near here.

1966 is probably not real. More likely, the reference bench marks to which these surveys were tied and which were assumed to be stable during this 1949-66 period, subsided about one-tenth of a foot (0.03 m) during the 17-year period.

Figure 12 shows a comparison of 1949 leveling by the National Geodetic

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Figure 12 near here.

Survey and 1970 and 1973 second-order leveling by the Geological Survey on a line extending from relatively stable ground west of Zamora across an area of fairly heavy pumping (fig. 4) east of Zamora to the valley trough at Knights Landing. For the 1973 survey, bench mark S849, which showed little change from 1949 to 1964 (fig. 6), was used as the stable reference tie. Although the data are only approximations, it appears that bench mark M859 about 2 miles (3 km) east of Zamora subsided about 2 feet (61 cm) between 1949 and 1973, and that bench mark F859 in the valley trough may have settled as much as 0.3 foot (0.09 m). In the area of bench mark M859 pumpage averaged about 1.0 foot (0.3 m) per year (fig. 4), but there is no record of long-term water-level change.

It is noteworthy that leveling control along the two lines running through areas of maximum water-level decline (fig. 3) on the east side of the valley--line 103 between Sacramento and Roseville (fig. 2) and lines 107 and 101 between Roseville and Marysville--show very little elevation change during an extended period of water-level decline. Actually the adjusted leveling data suggest slight uplift for most bench marks during the elapsed interval.

METHODS OF ESTIMATING FUTURE SUBSIDENCE

In general, two different methods are available for estimating future subsidence caused by water-level decline. Both approaches require considerable specific data, and calculations are only as reliable as are the basic data used. The most direct method is to calculate the subsidence/head-decline ratio for periods of recorded subsidence and water-level change, and to project this relationship into the future. This ratio can be calculated either on an areal basis from subsidence and water-level change maps or at individual locations from bench-mark graphs or compaction-recorder graphs and representative hydrographs. In using this method, three considerations are essential: (1) the head-decline records must be truly representative of the stress increase in the compacting zone of the aquifer system, (2) only head declines that exceed previous low water levels are relatable to current subsidence, and (3) because of a time lag, ultimate subsidence is seldom attained, therefore, predictions of future subsidence based on the subsidence/head-decline ratio tend to be too low.

The second method for estimating subsidence, S , at a given location is from the following equation:

$$S = k \cdot m \cdot \Delta p'$$

where k = the average compressibility of the compacting beds,

m = thickness of the compacting beds, and

$\Delta p'$ = change in effective stress resulting from water-level change.

C-040817

In this equation, S is ultimate subsidence for the given $\Delta p'$. In nearly all prior papers (USGS) using the symbol p for stress, p represents geostatic stress and p' the effective stress. See especially Water-Supply Paper 2025, p. IV, *Symbols*.

Subsidence results from the compaction of compressible water-bearing deposits due to increased stresses caused by a water-level decline. The magnitude of the subsidence is dependent on the effective-stress increase, the compressibility and thickness of the individual beds, the time the stress is applied, and also, on the past history of stress--whether the increased stress is being applied for the first time or has been attained or exceeded previously. Poland (1969) discusses the parameters needed to predict subsidence from field and laboratory data, and Riley (1969) describes the type of stress-strain interpretation of an aquifer system that can be made with adequate data.

Depending on the nature of the deposits, compaction may be (1) largely elastic (Poland, Lofgren, and Riley, 1972, p. 3), in which case stress and strain are proportional, independent of time, and reversible, or (2) principally nonelastic, resulting from a rearrangement of the granular structure in such a way that the volume of the deposits is permanently decreased. In general, if the deposits are coarse sand and gravel, the compaction will be small and chiefly elastic and reversible, whereas if they contain fine-grained clayey beds, the compaction will be much greater and chiefly inelastic and permanent. In either case, a one-directional compression of the deposits occurs which results in a subsidence of the land surface.

Considering the last term in the equation above, changes in ground-water levels may change effective stresses in two different ways (Lofgren, 1968):

1. A change in the position of the water table changes the effective stress, due to the increase or decrease in buoyant support of grains in the zone of the change; this change in gravitational stress is transmitted downward to all underlying deposits.
2. A change in position of the water table, or the piezometric surface, (artesian head) or both, that induces vertical hydraulic gradients across confining or semiconfining beds produces a seepage stress which is algebraically additive to gravitational forces and thereby changes the effective stress in the deposits. A change in effective stress also results if a natural preexisting seepage stress is altered in direction or magnitude by a change in head.

Where adequate lithologic, hydrologic, and compressibility data are available, the compacting zone, if known, can be segmented into lithologic units and appropriate values of compressibility, thickness, and stress change applied to each segment. In the Sacramento Valley, however, these hydrogeologic parameters are not known. Few well-defined lithologic units have been mapped, and the gross compressibility of even the best defined beds is not known. To estimate future subsidence from existing data anywhere in Sacramento Valley one would have to assign crude numbers to the various parameters of the above equation, which probably would give answers no better than those derived from borrowing subsidence/head-decline ratios from areas of the San Joaquin Valley.

Since water-level declines are responsible for the stresses that cause subsidence, the following general criteria can be applied to areas of possible subsidence:

(1) Where little or no decline in water level has occurred, in either the confined or unconfined aquifers, no subsidence is expected. If all of the deposits in the aquifer system are coarse grained, little measurable subsidence should occur. Also, even if fine-grained aquitards occur in the aquifer system, little subsidence is expected until preconsolidation stresses (Poland, Lofgren, and Riley, 1972, p. 7) are exceeded.

(2) Where increase in stress has caused measurable subsidence, further stress increases will cause continued subsidence. The calculated subsidence/head-decline ratio or subsidence/stress ratio of the period of measured subsidence is the simplest and may be the most practical method of estimating future changes.

(3) Where water levels have declined, and then recovered significantly, the subsidence/head-decline ratio has little significance until water levels return to their former low levels.

(4) As in the San Joaquin Valley, the subsidence/head-decline ratio may not be a reliable parameter for predicting future subsidence until the head in the compacting zone has declined more than 100 feet below prepumping levels. Generally, this ratio is too small during the early stages of pumping decline. Since historic water-level declines throughout most of Sacramento Valley have been considerably less than 100 feet, subsidence/head-decline ratios in most areas may not be too meaningful.

SUMMARY AND CONCLUSIONS

Land subsidence is known to occur in several areas of ground-water overdraft, and probably affects other areas not now recognized. East of Zamora, for example, as much as 2 feet (0.6 m) of subsidence has been measured, and west of Arbuckle a water-level decline of more than 110 feet (33 m) probably has caused about 2 feet (0.6 m) of subsidence. In at least six poorly defined areas of substantial pumping drawdown (fig. 3), comprising probably a third of the valley floor south of Sutter Buttes and about 100 square miles (260 km^2) north of Willows, measurable land subsidence may have accompanied the intensive pumping of ground water.

Although a rather extensive network of precise leveling by the National Geodetic Survey exists in Sacramento Valley, few areas have sufficient control to delineate the magnitude and extent of possible subsidence that may have occurred. Along the few lines of leveling where repeated surveys have been made, adjustment problems and complications of reference datums make a precise interpretation of elevation changes impossible. A cursory review of the valleywide leveling data suggests that inaccuracies of a tenth of a foot or more probably exist in some of the published elevations. It is concluded that the first leveling of the valleywide network, largely completed before the heaviest ground-water development in the valley, is a worthy base for measuring subsequent land-surface changes, and that most of the discrepancies in the leveling data are due to adjustment problems in resurvey data along the various lines.

If problems of land subsidence are of concern in Sacramento Valley, and especially if estimates of subsidence potential in various parts of the valley are needed, it is suggested that serious consideration be given to the following types of data collection and interpretation:

a. It is believed that a detailed reinterpretation of the original field data of repeated surveys by the National Geodetic Survey, possibly by the National Geodetic Survey itself, could greatly improve the accuracy and value of these data. Instead of warping the data to indicate bench-mark stability, all elevations should be considered as "floating." Thus, relative changes from stable areas to subsiding areas could be calculated.

C-040824

b. Short resurveys along established lines of the network, extending from bedrock or areas of stability to areas of possible subsidence, could measure the amount of change that has occurred in areas where no information is now available. Second-order accuracies on these resurveys would be adequate to define subsidence rates needed in a more thorough appraisal of the valley. Several lines that might be considered are:

(1) From bench mark S849 west of Zamora to Williams (fig. 7). Reportedly local canal surveys west from Arbuckle could be rerun to give control in this area of maximum water-level decline.

(2) From bench mark S849 west of Zamora to Davis (fig. 5). At bench mark A644, near Zamora on this line, six-tenths of the subsidence has occurred since 1964 (compare fig. 12 with fig. 5).

(3) From bedrock north of Chico southward into the center of pumping south of Chico.

(4) From bedrock east of Marysville to Marysville and then southeast through the area of maximum pumping and water-level decline.

(5) East and west along the highway south of Sutter Buttes, using the Buttes as a stable tie.

(6) Northeast of Sacramento, through Roseville, thence north through an area of steady ground-water decline, but no leveling since 1947-48.

c. New lines of bench-mark control, running from stable ties into the following areas of suspected subsidence, could be established for future monitoring:

(1) From the foothills east of Marysville westward through the pumping hole shown in figure 3.

(2) From 10 miles north of Willows, a line due west to the foothills and due east to the foothills southeast of Chico, passing through two areas of intensive pumping.

d. Compaction and water-level recorders in a few known subsidence areas could supply stress-strain parameters needed in estimating future subsidence.

e. Laboratory time-consolidation tests on cored samples of selected fine-grained deposits might be considered.

Without these kinds of additional data, a more detailed interpretation of the magnitude and rate of subsidence in Sacramento Valley, both past and future, will be difficult.

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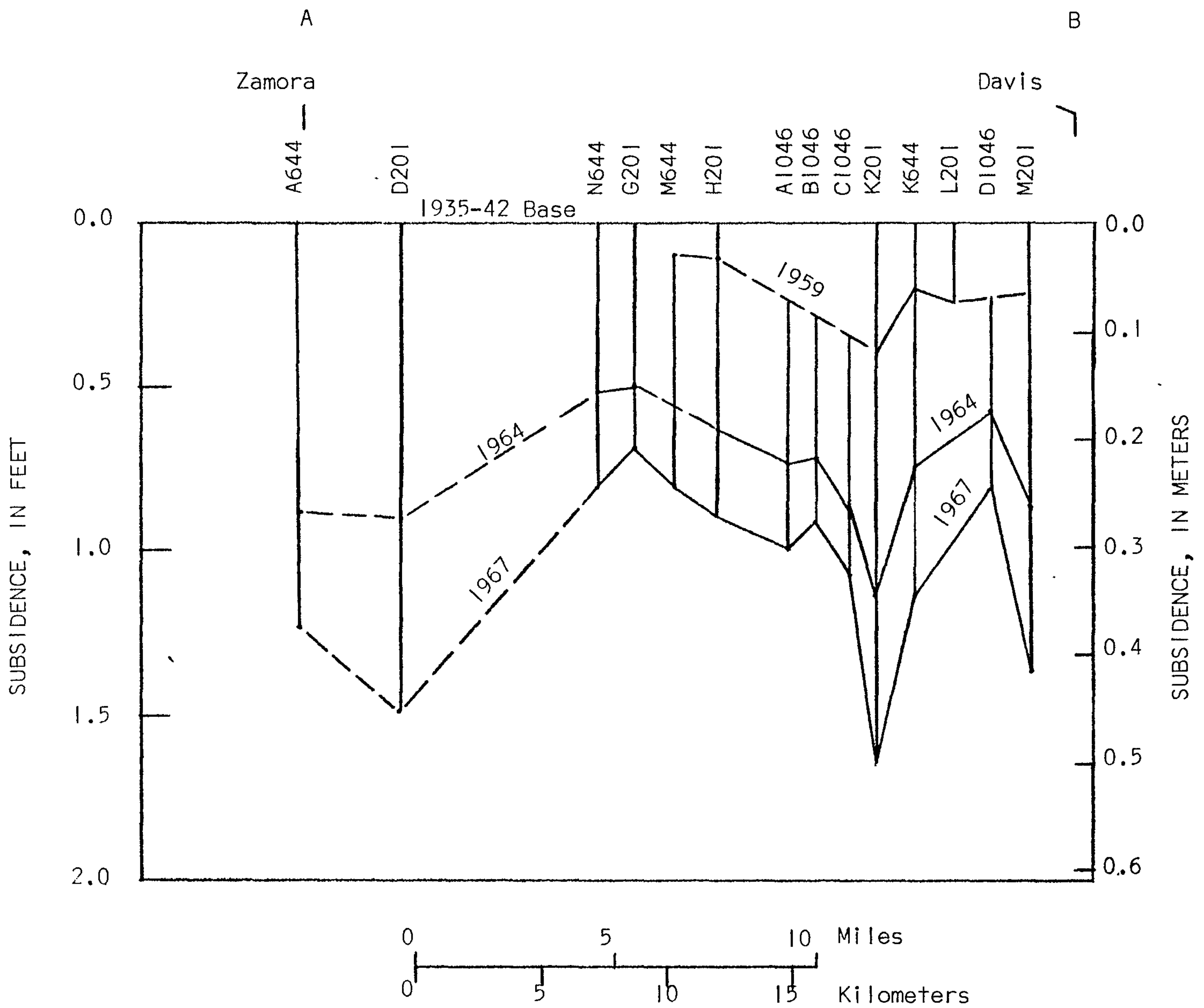

Figure 5.--Profiles of apparent land subsidence, A-B, 1935-42 to 1967, from Zamora to Davis. For location, see figure 1.

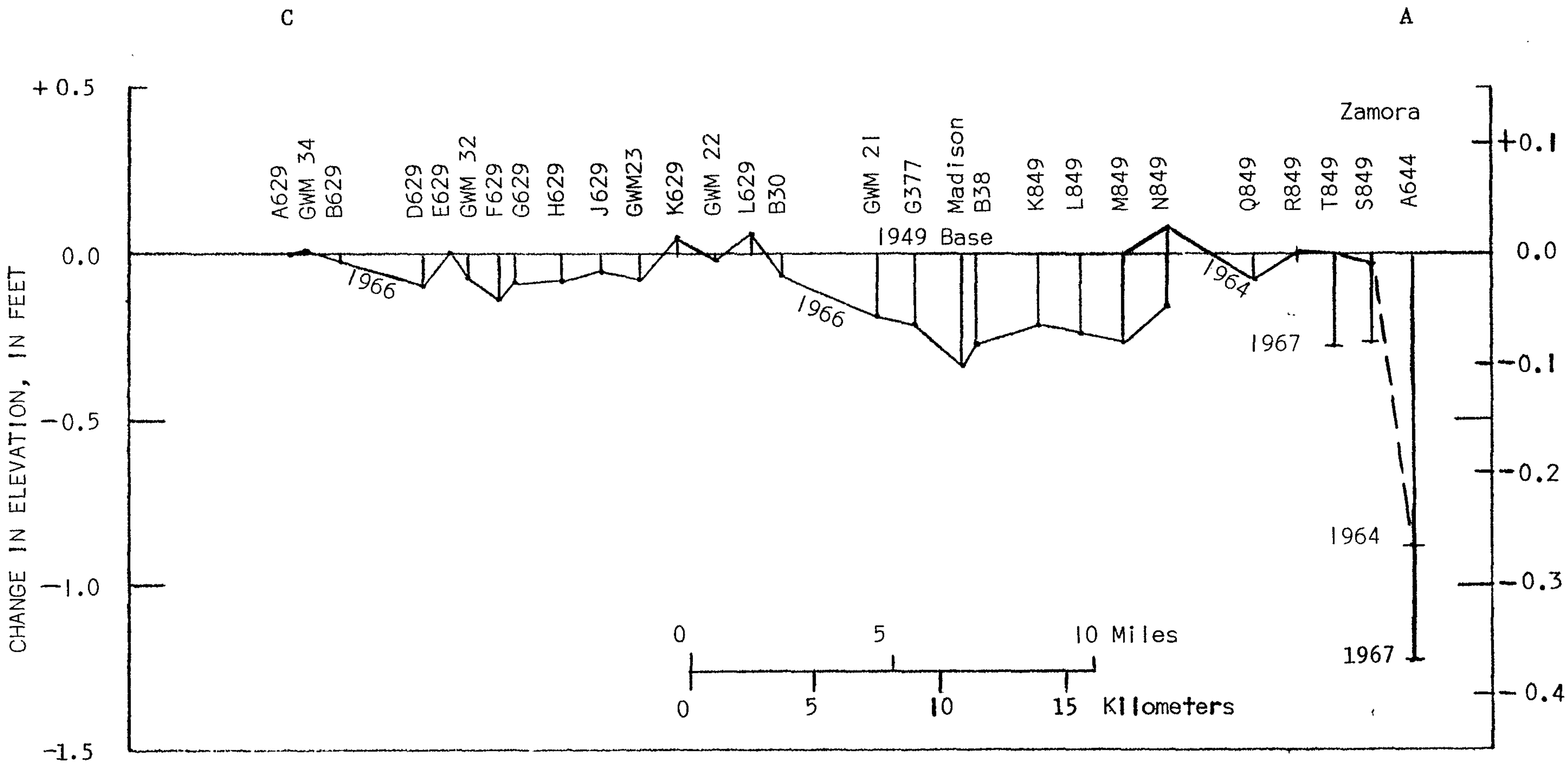

Figure 6.--Profiles of apparent land-surface change, C-A, 1949 to 1964 and 1966, from 28 miles southwest of Zamora to Zamora. For location, see figure 1.

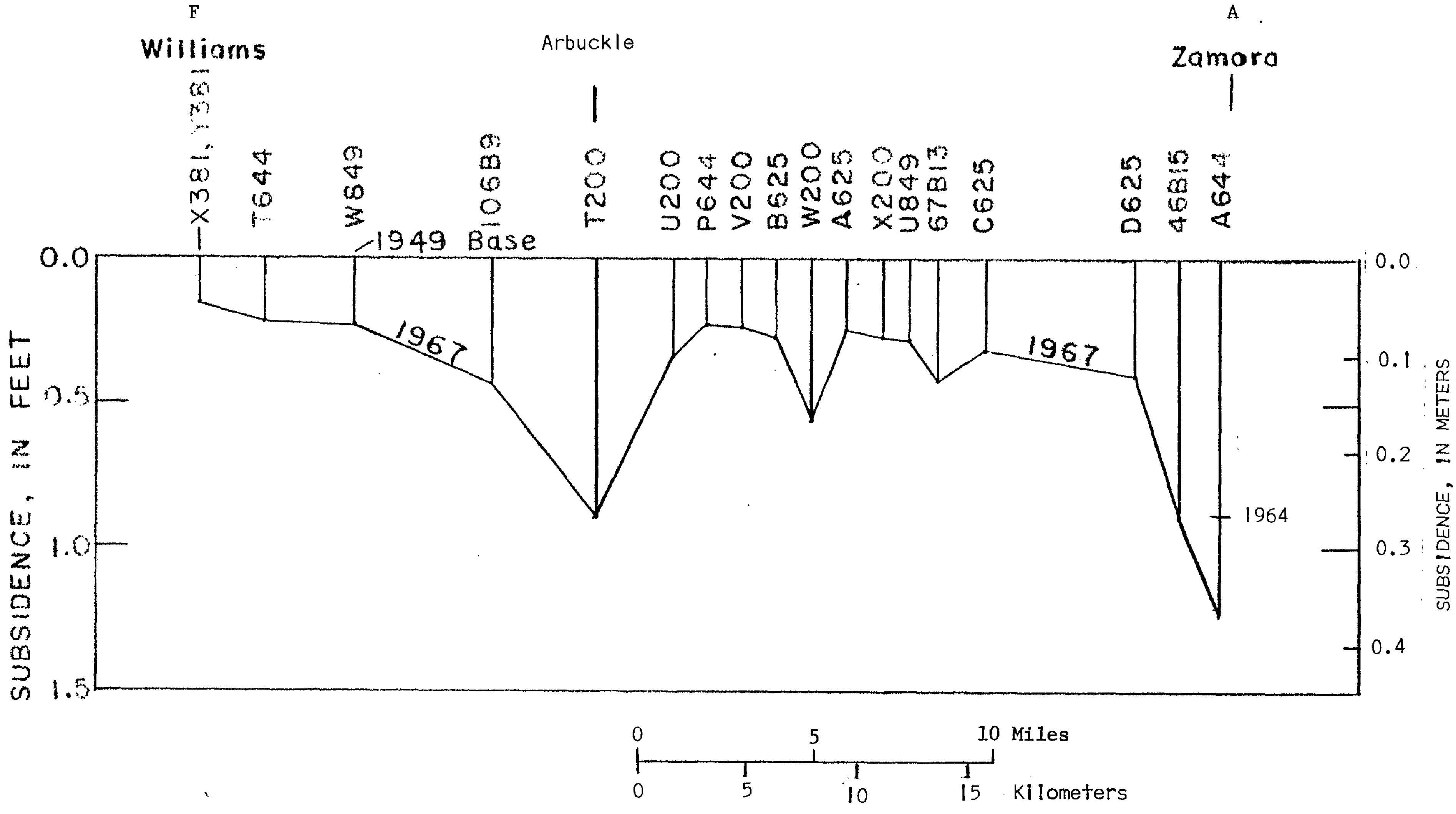

Figure 7.--Profiles of apparent land subsidence, F-A, 1949 to 1967, from Williams to Zamora. For location, see figure 1.

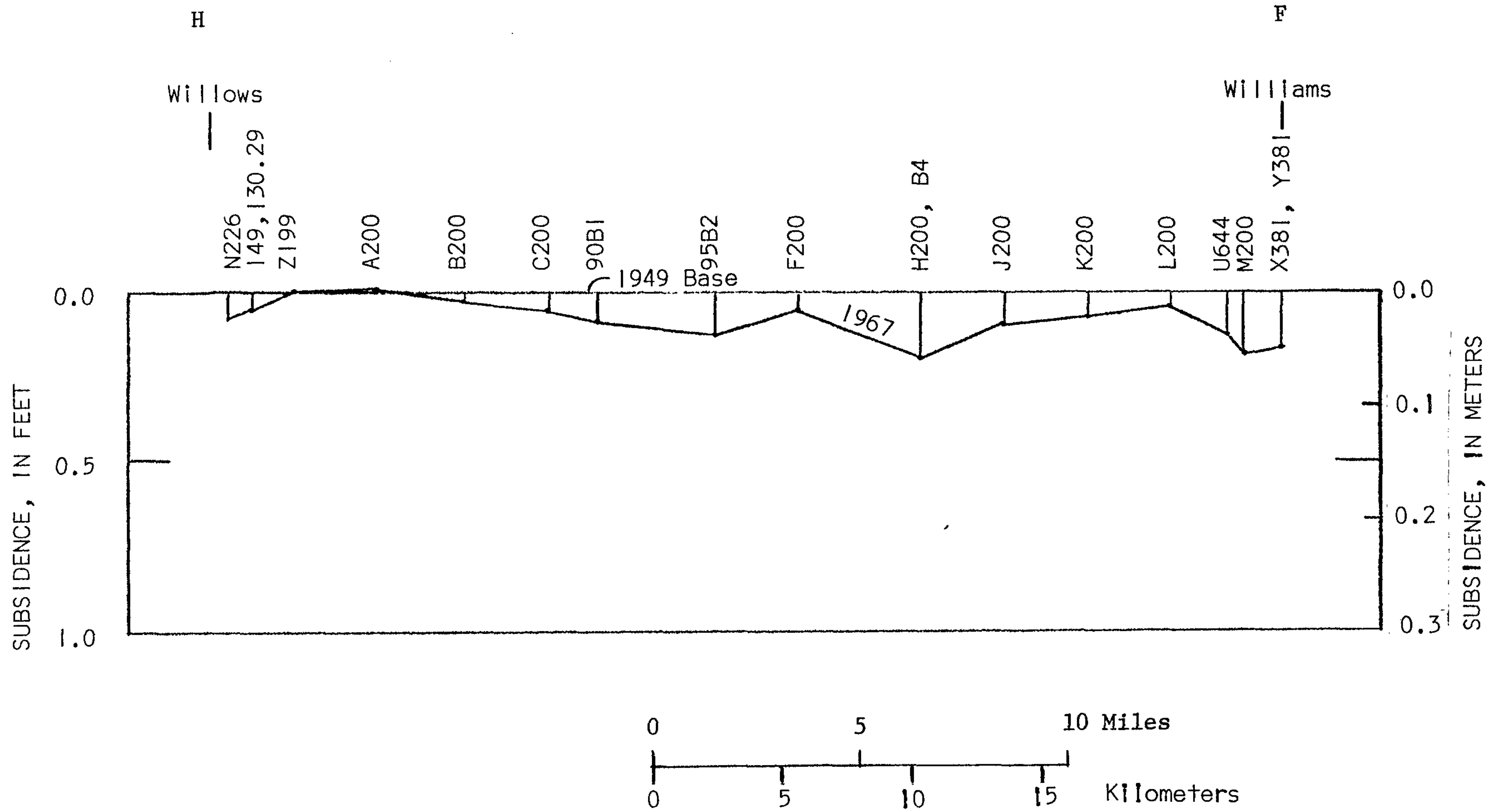

Figure 8.--Profiles of apparent land subsidence, H-F, 1949 to 1967, from Willows to Williams. For location, see figure 1.

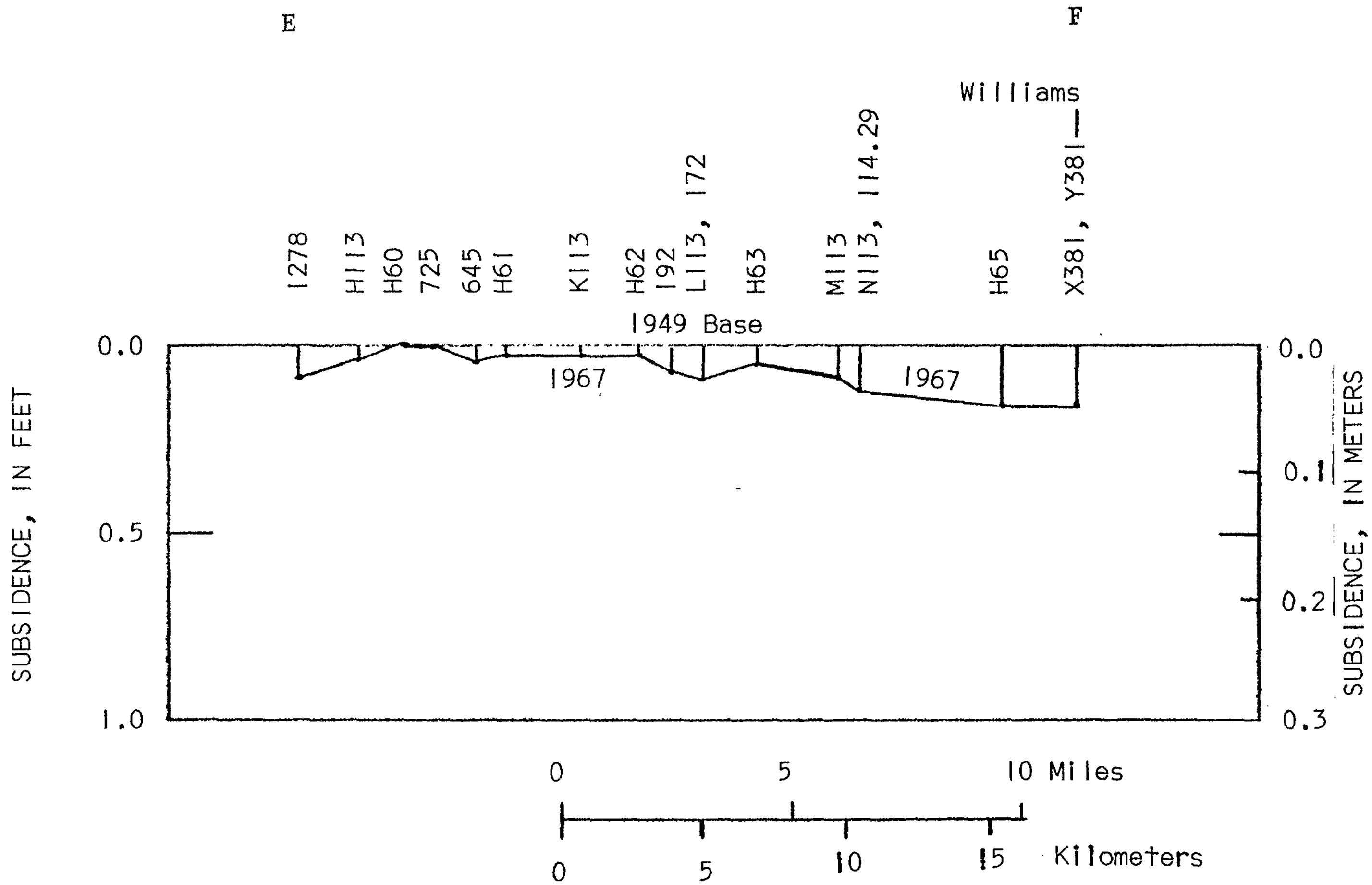

Figure 9.--Profiles of apparent land subsidence, E-F, 1949 to 1967, from 17 miles west of Williams to Williams. For location, see figure 1.

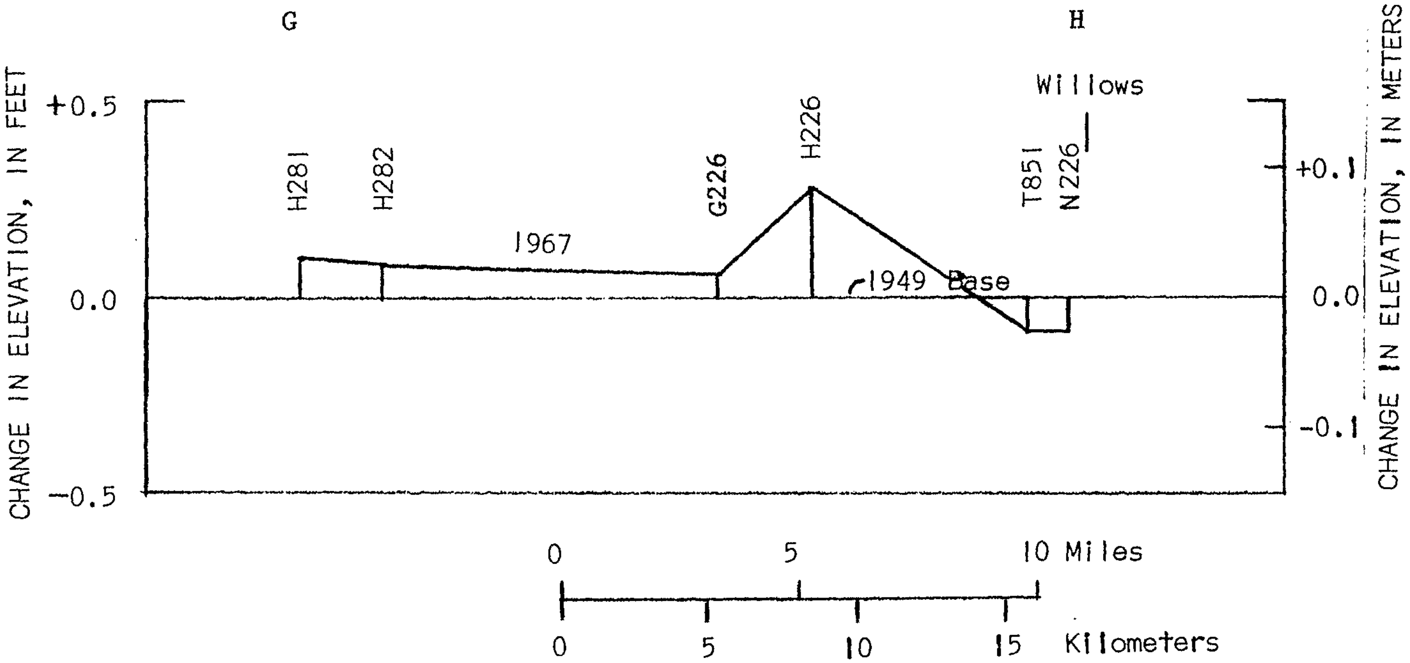

Figure 10.--Profiles of apparent land-surface change, G-H, 1949 to 1967, from 16 miles west of Willows to Willows. For location, see figure 1.

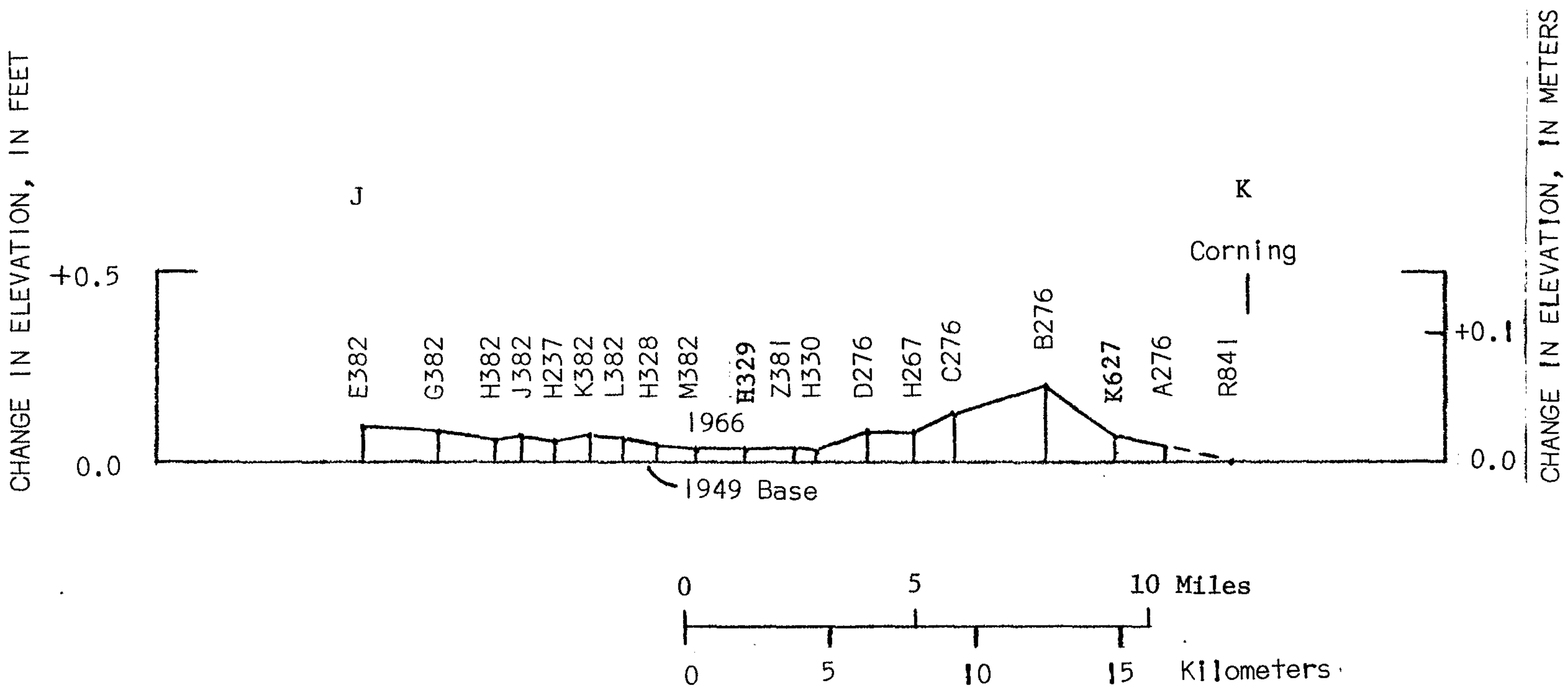

Figure 11.--Profiles of apparent land-surface change, J-K, 1949 to 1966, from 19 miles west of Corning to Corning. For location, see figure 1.

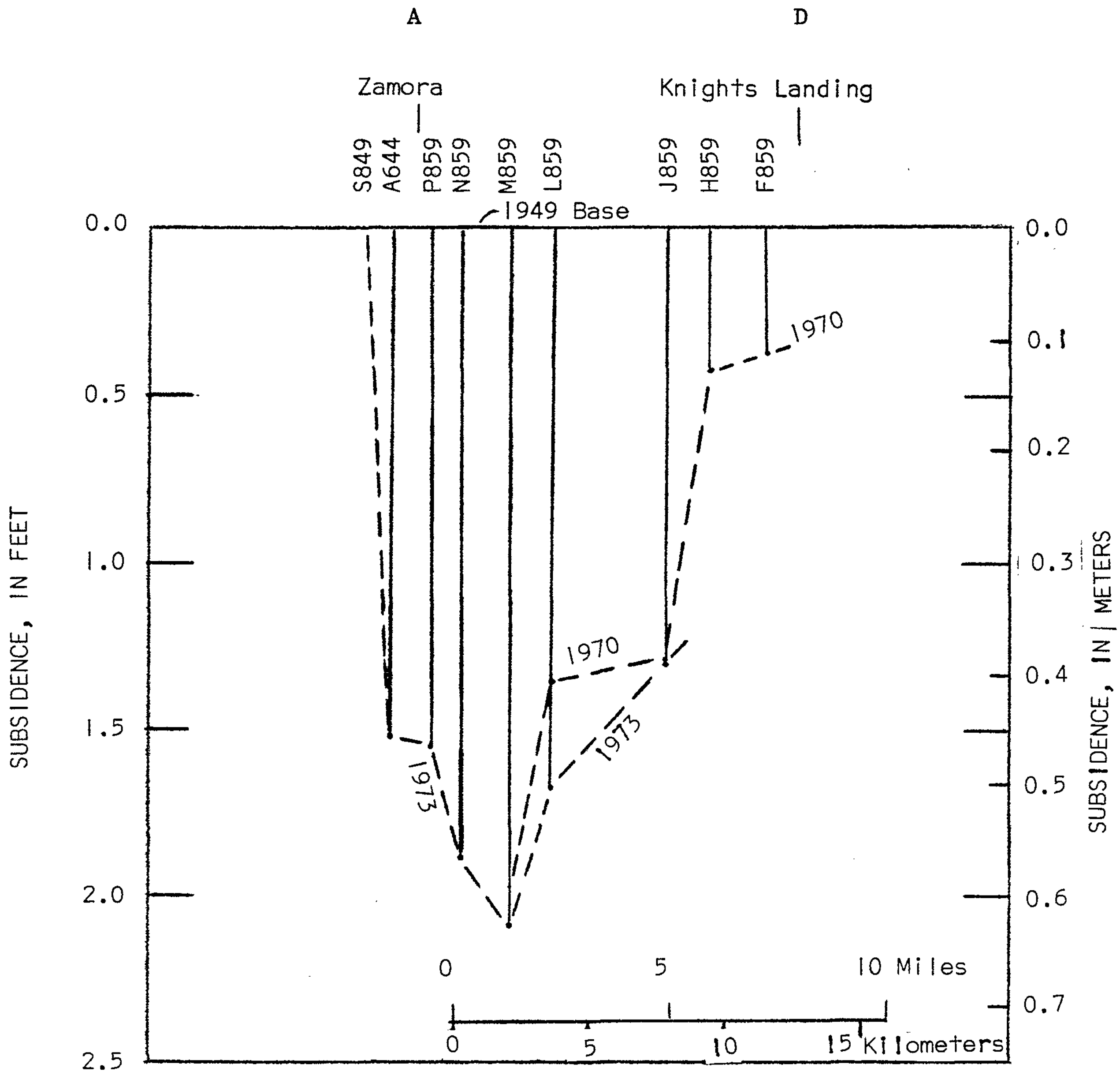

Figure 12.--Profiles of apparent land subsidence, A-D, 1949 to 1970 and 1973, from Zamora to Knights Landing. (1949 leveling by National Geodetic Survey; 1970 and 1973 second-order leveling by U.S. Geological Survey.)

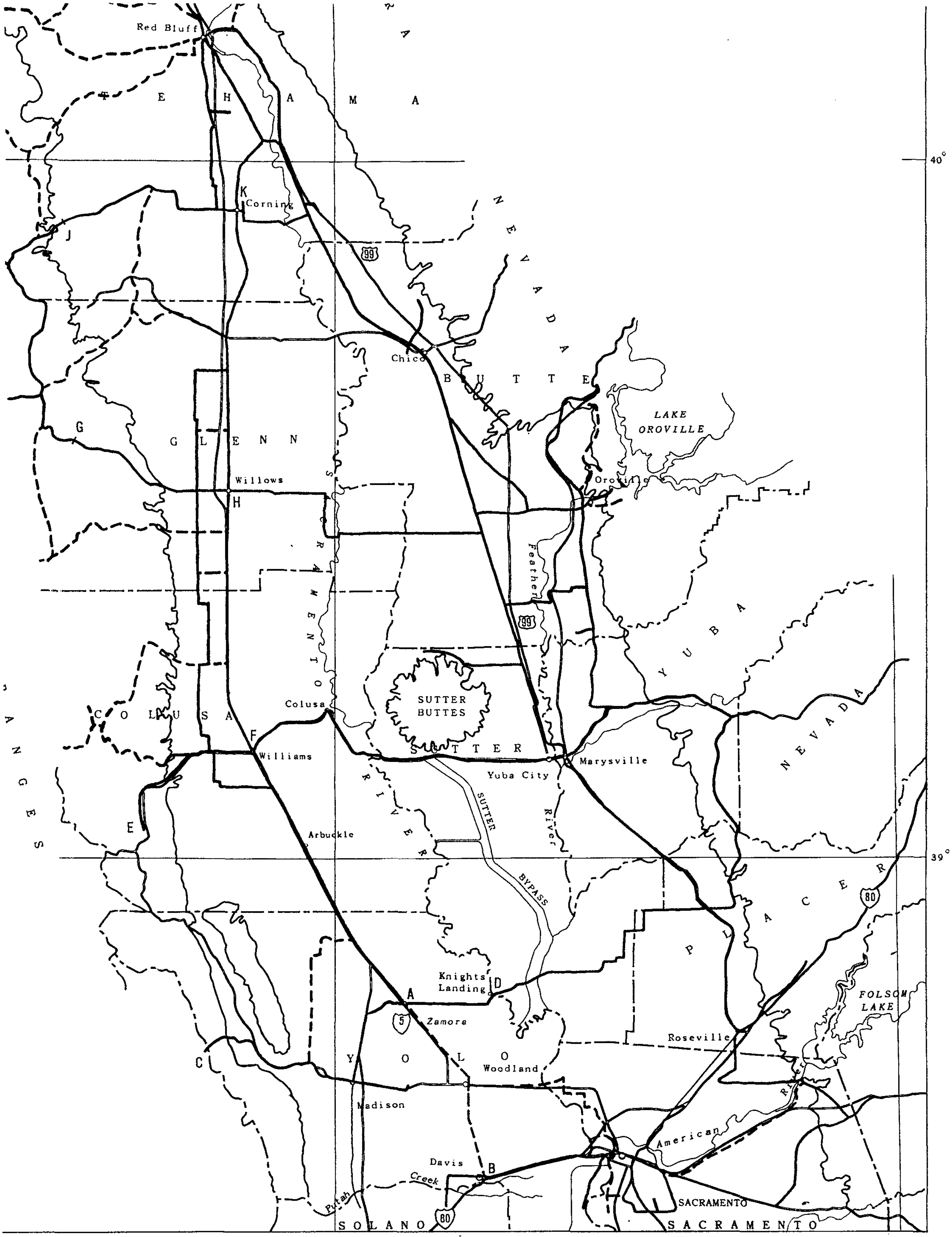

FIGURE 1.—Network of regional leveling by the National Geodetic Survey, Sacramento Valley, California

0 10 20 30 MILES

0 10 20 30 40 KILOMETERS

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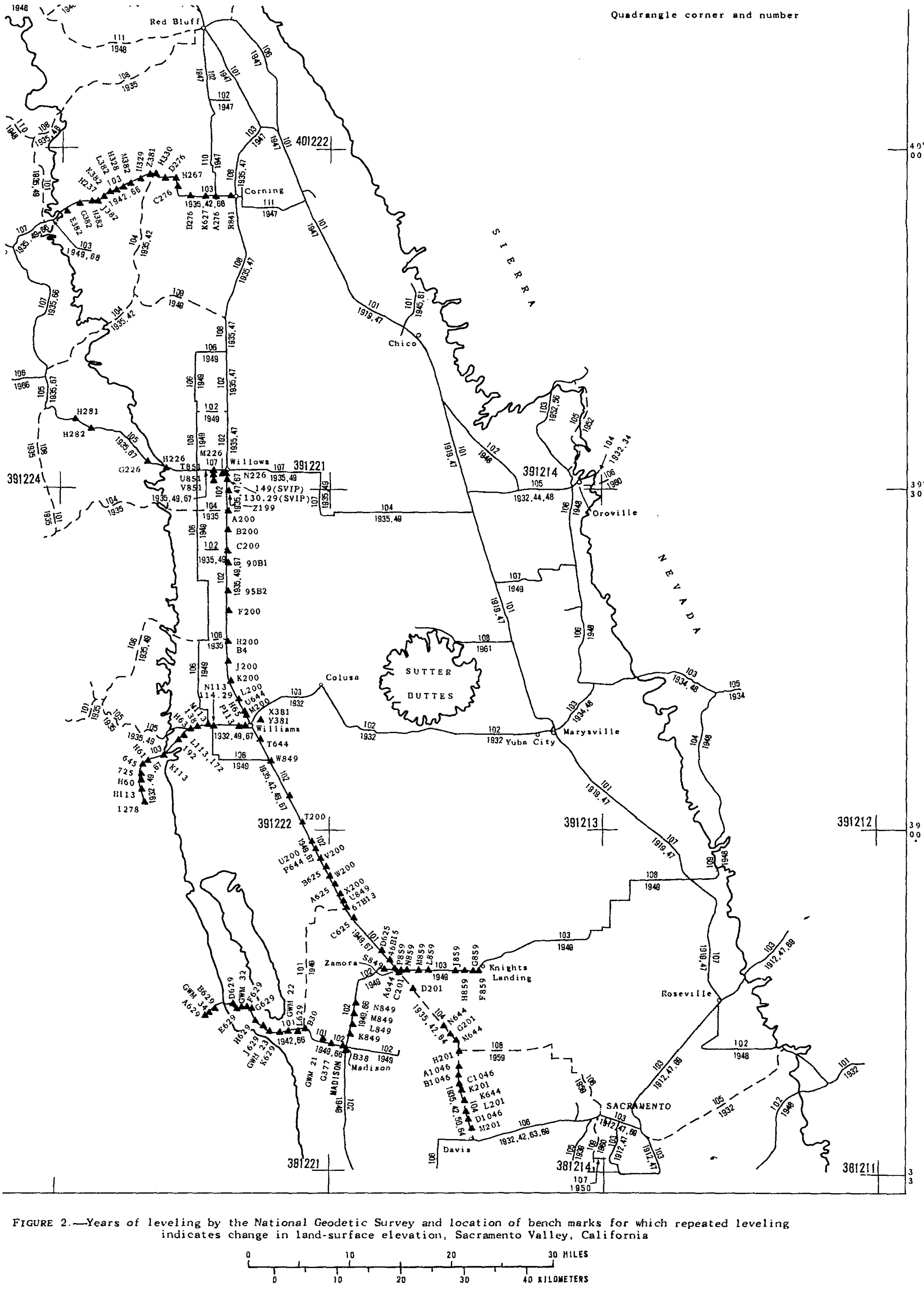

FIGURE 2.—Years of leveling by the National Geodetic Survey and location of bench marks for which repeated leveling indicates change in land-surface elevation, Sacramento Valley, California

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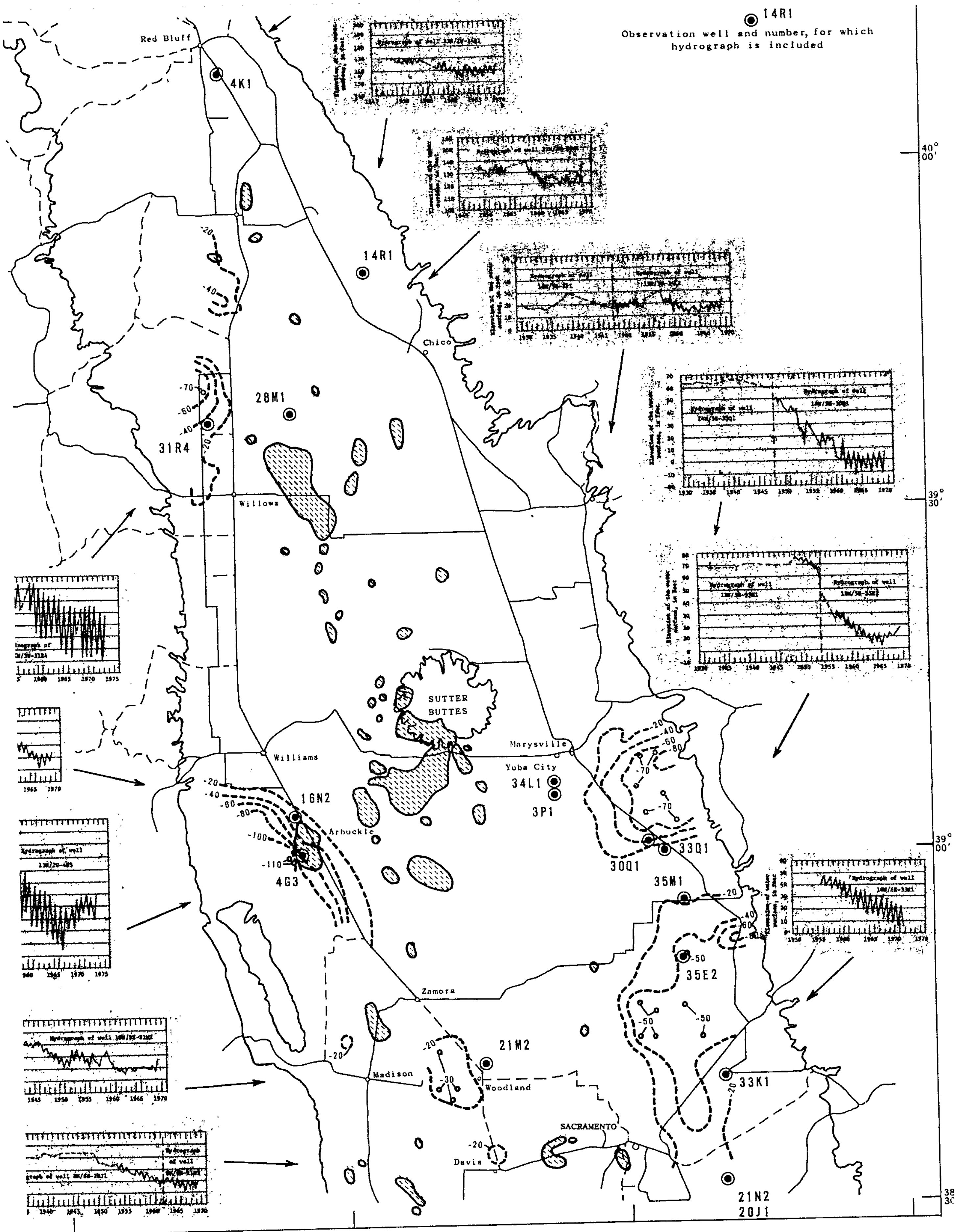

FIGURE 3.—Areas of significant water-level decline, gas fields, and network of regional leveling with hydrographs of observation wells, Sacramento Valley, California

C-040839

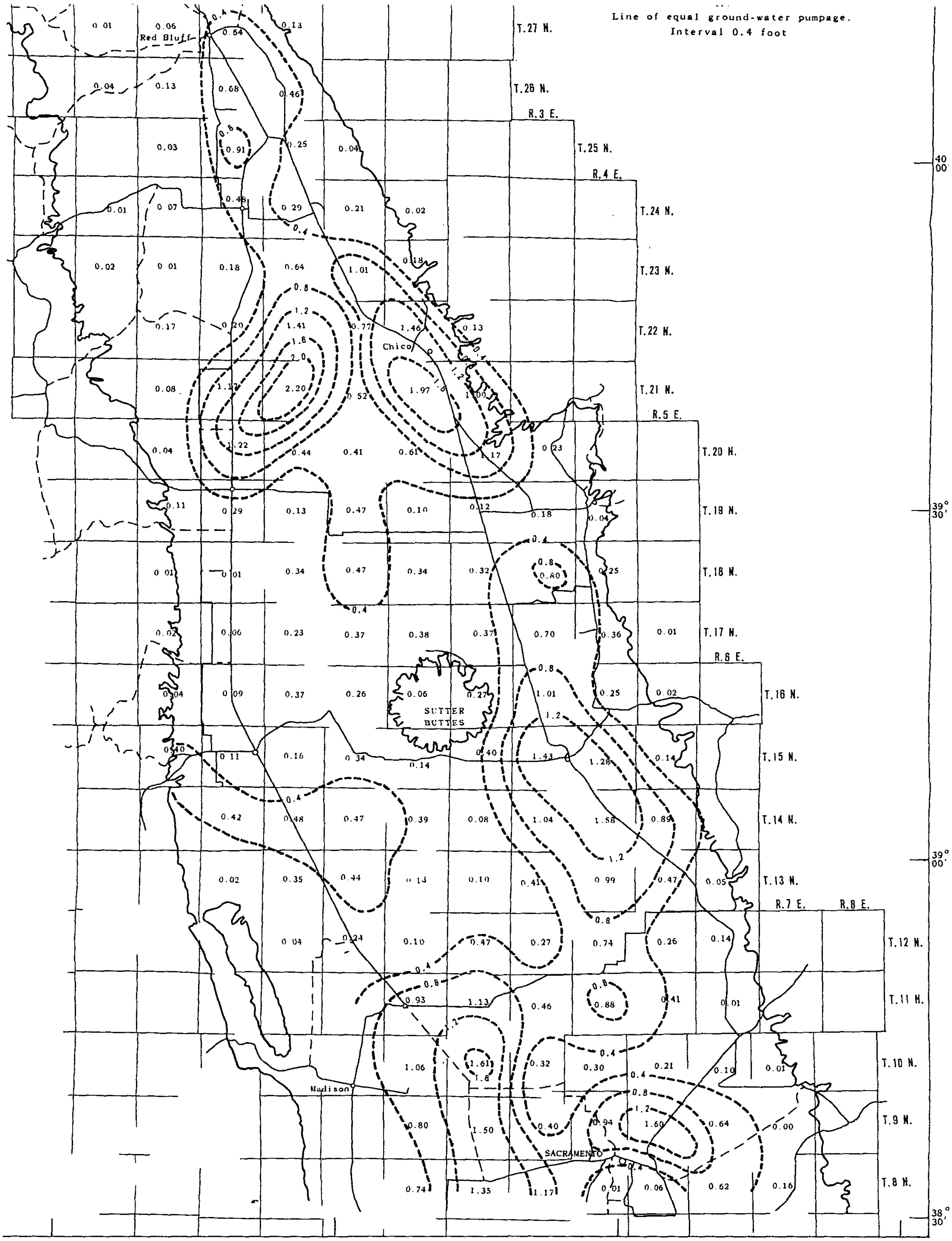

FIGURE 4.—Average annual ground-water pumpage by township, in feet, 1966–69, Sacramento Valley, California

0 10 20 30 MILES
0 10 20 30 40 KILOMETERS

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